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Semtner, Albert J.

Monterey, California. Naval Postgraduate School

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SCIENTIFIC DEVELOPMENT OF A MASSIVELY PARALLEL OCEAN CLIMATE MODEL

A Final Report to the U.S. Department of Energy (DOE)

for the CHAMMP Program on Climate Research
(Computer Hardware, Advanced Mathematics, and Model Physics)

by

Albert J. Semtner, Naval Postgraduate School (NPS)
Department of Oceanography; Monterey, CA 93943

and

Robert M. Chervin, National Center for Atmospheric Research (NCAR)
Climate and Global Dynamics Division; Boulder, CO 80307-3000

Synopsis. Over the last three years, very significant advances have been made in refining the grid resolution of ocean models and in improving the physical and numerical treatments of ocean hydrodynamics. Some of these advances have occurred as a result of the successful transition of ocean models onto massively parallel computers, which has been led by Los Alamos investigators. Major progress has been made in simulating global ocean circulation and in understanding various ocean climatic aspects such as the effect of wind driving on heat and freshwater transports. These steps have demonstrated the capability to conduct realistic decadal to century ocean integrations at high resolution on massively parallel computers.

Specifics

1. Examination of ocean response to different wind stress and buoyancy prescriptions

One of the scientific goals of our original CHAMMP funded research was to investigate the response of the global ocean to changes in wind stress and buoyancy fluxes. An opportunity presented itself to conduct further integrations with our 1/2-degree global ocean model using new analyzed wind fields of the European Centre for Medium-Range Weather Forecasts (ECMWF). These integrations were run at no cost to DOE on a CRAY Y-MP/2 of the Model Evaluation Consortium for Climate Assessment (MECCA). Three successive integrations were undertaken to simulate global ocean circulation on a 1/2-degree grid: first with ECMWF monthly climatological winds of 1980-89, second with individual monthly winds of the period, and finally with daily winds. The last of these simulations only finished in late December of 1993. The simulations have shown tremendous time variations in key climatic quantities such as ocean heat transport across 24 N in the Atlantic and Pacific. Results are being analyzed and compared with observations such as those of Hall and Bryden (1982) and Bryden et al. (1991). Some traditional assumptions about steadiness of deep transport and the degrees of seasonal and interannual change in total heat transport are found to be questionable; and new estimates of heat transport and variability have been obtained. These findings are being submitted to the Journal of Geophysical Research, as follows:

- (i) On the Computation of Meridional Ocean Heat Transport from Hydrographic Sections, by R.M. Chervin, A.P. Craig, and A.J. Semtner;
- (ii) Sensitivity and Variability of Meridional Ocean Heat Transports from a Global Ocean Model, by R.M. Chervin, A.P. Craig, and A.J. Semtner

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In ongoing investigations with the global 1/2-degree model, it became important to determine the influence of robust-diagnostic forcing with a three-year time scale below the depth of the main thermocline (710 m) as well as in the polar regions. This process certainly could be expected to reduce eddy energy somewhat, but the effect on the time-mean circulation was unclear. On the one hand, the constraint to gridded Levitus data might be maintaining some features of the deep circulation; but on the other hand, the Levitus (1982) data are so smoothed in space that net damping of circulation might result. To examine the issues, subsurface forcing was removed in all but the polar regions and in the immediate vicinity of the Strait of Gibraltar. The final five years of the earlier integration were repeated (with NSF support for use of the CRAY Y-MP/8 at NCAR), and the results were analyzed in a systematic fashion. The significant result for the time-mean circulation was a strengthening of the deep western boundary currents in the Atlantic and Pacific, with enhanced overturning to 15 Sv in the North Atlantic and further penetration of abyssal water into the North Pacific. The eddy kinetic energy increased somewhat but not enough to match Geosat energy levels, as reported in a comparison of the fields by Wilkin and Morrow (1993). The overall findings have just recently been summarized in a paper by Semtner (1993).

2. Development of a free-surface '1/4-degree' model with realistic geometry and forcing

In order to be able to use massively parallel computers efficiently (by removing previous non-local line integrations around islands), as well as to improve the physical representation of a key observable ocean variable, it had been proposed to implement a free-surface formulation in the global model. The 1/2-degree model provided the testing ground for a free-surface formulation of Killworth, Webb, et al. (1991). The modifications provided by Peter Killworth for the Cox (1984) model were easily adapted to the formulation of Chervin and Semtner (1990), since both formulations derive from the common vectorizable version of the GFDL (Bryan, 1969) model constructed by Semtner (1974). Early testing of the method showed the presence of a slowly growing instability in surface pressure, which was easily remedied after it was diagnosed.

As was proposed in the original CHAMMP request, the resolution requirements for realistic global modeling were to be investigated. A 1/4-degree (average) grid was selected to continue global simulations with the free surface, because of the known deficiencies of the 1/2-degree model in representing instabilities at high latitudes. A Mercator grid was chosen with 0.4 degrees longitudinal spacing, thereby produced an everywhere square grid with average size of 0.26 degrees between the equator and latitude 75 degrees. Because of the cosine-of-latitude factor, the gridsize becomes progressively smaller at high latitudes, in rough proportion to the decreasing radius of deformation, to permit better eddy resolution. The choice of this grid was related also to the fact that the 1/4-degree configuration had the largest mesh that would fit efficiently into NCAR's CRAY Y-MP/8 with a solid-state disk of 256 megawords. The model runs at 1.2 Gigafllops in a stand-alone multitasking class and uses NSF computing resources allocated to Chervin to match his CHAMMP support and to Semtner for research associated with the World Ocean Circulation Experiment (WOCE).

A new geometry for the global model was produced from bathymetric data available at a nominal resolution of 1/12 degree. Because of the use of a free surface rather than a rigid lid in the model formulation, there was no need for topographic smoothing except to the local gridsize. This was an unexpected but extremely important benefit from the method, which was first noted by Los Alamos collaborators developing a similar method. Lateral friction and diffusion coefficients were weighted by the cosine squared of latitude to reduce damping effects at smaller gridsize. An interpolated tape of instantaneous temperature and salinity from the most recent 1/2-degree run without deep restoring was produced, using Levitus data or filling laterally where necessary to define values

within the new 1/4-degree grid at all 20 vertical levels. The model was quickly initialized to these fields by using rapid robust-diagnostic forcing with a 5-day time constant for a first month of integration with January 1985 winds. Then the model continued forward with no deep restoring other than in polar regions and near Gibraltar, using spline-interpolated ECMWF monthly wind stresses for the period February 1985 through December 1989. That integration was completed in November of 1993.

3. Examination of the effects of improved (1/4) resolution and physics

A complete analysis of the 1/4-degree simulation with 1985-89 winds is now underway. A one-year preliminary analysis in early 1993 for the period April 1985 through March 1986 was conducted to indicate whether the simulation was proceeding properly. Some interesting aspects of the new integration, which are very realistic, are greater meridional overturning in both hemispheres, continued flow through a complex Indonesian Archipelago, quite vigorous Agulhas eddies extending well toward South America, a Gulf Stream that tends to separate mainly at Cape Hatteras, and much increased eddy kinetic energy in the Southern Hemisphere.

Already, a complete archive of statistically processed tapes has been produced by Robin Tokmakian of NPS; and model output is being made available to many interested scientists to maximize the scientific analysis and interpretation. In all, some 20 groups have now requested access to model output and been given the necessary guidance to obtain it. These include oceanographers at university sites such as Columbia, Hawaii, Duke, Oregon State, MIT, Texas A+M, Scripps, and Colorado, as well as in US research labs like JPL, GISS, GSFC, PMEL, AOML, and ERL and laboratories in Australia, New Zealand, France, Canada, South Africa, Germany, and China. One of the most active analysis efforts that is now underway, emphasizing both the comparison of surface height with TOPEX satellite altimetry and the evaluation of N. Pacific acoustic long-line transmissions, is that of Carl Wunsch, Detlef Stammer, and others at MIT. Recently, Stammer provided us with some feedback on the model run. Model variability in surface height was compared with TOPEX variability, using identical color bars and spatial resolution. The agreement between the two was especially good in the eddy-active regions of the Southern Hemisphere. This leads us to believe that the model is not far from having the right resolution in many parts of the global domain. It also provides hypotheses about possible causes of disagreement in some western boundary currents and quiescent areas (due to simplified heat flux prescriptions and to the lack of daily wind forcing). Ongoing comparisons of mean surface height and seasonal fluctuations continue to show good agreement between the model results and TOPEX altimetry.

Following a definitive analysis of the 1/4-degree results by the standard techniques used in earlier efforts, a comprehensive paper ~~are~~ is being submitted for publication by Semtner and Chervin near ~~the~~ the end of the present proposal period. In the meantime, a new videotape of highlights from the global model was produced by Shirley Isakari at the Naval Postgraduate School, and it has been copied and distributed to over 140 scientists. The video built upon the expertise developed in three previous ocean animation efforts at the Postgraduate School using software written by Michael McCann. The new tape shows five-minute sequences of global rotating surface height, near-surface temperature and salinity, and the magnitude of the vertically integrated flow, plus one-minute sequences of near-surface salinity in six eddy-active regions. The new animations clearly demonstrate the enormous progress toward realism that has been accomplished by moving to higher resolution, a free surface, unsmoothed geometry, and observed interannually varying winds.

4. Extension to 1/6-degree (with LANL) using the Parallel Ocean Program

A major effort in global ocean modeling is now building on the previous research at 1/2 degree and at 1/4 degree on average. It is doubly significant in that it extends the earlier integrations well into an

eddy-resolving regime and demonstrates conclusively the viability of massively parallel computer architectures. In collaboration with CHAMMP investigators Robert Malone, Richard Smith, and John Dukowicz of the Los Alamos National Laboratory, a 1/6-degree (average) model extending from 78 S to 78 N has been constructed. Longitudinal grid spacing is 0.27 degrees and latitudinal spacing averages 0.17. The model uses the LANL Parallel Ocean Program (POP), a free-surface code mainly in Fortran 90, which incorporates many features of the model of Chervin and Semtner (1990) and the GFDL/MOM model of Pacanowski et al. (1991). Additional information on the model, including description of major improvements over previous models, can be found in Smith et al. (1992) and Dukowicz and Smith (1993). The 1/6-degree model runs on 256 nodes of the 1024-node Connection Machine 5 at Los Alamos, 300 times as fast as real time.

High resolution bathymetry and analyzed ECMWF winds were produced by Anthony Craig at NCAR; and time- and space-interpolated winds for the 1/6-degree run as well as initial conditions for a rapid start were produced by Isakari at NPS. The 1/6-degree simulation was initialized with interpolated 1/4-degree 1988 results from NPS and restarted with January 1985 wind fields for the integration that now has been completed through June 1993. At the time of this proposal writing, a very active analysis phase is underway, in order to understand the complete dynamic and thermodynamic behavior of the model ocean. Preliminary indications are that the simulation has been incredibly successful in reproducing a large variety of phenomena that are found in the real ocean and have important effects on climate. Early efforts at NPS have concentrated on using animation to examine the rich turbulent structures throughout the Southern Ocean and in the Indian Ocean. A manuscript on significant early findings from the analysis is being submitted to Science Magazine by Smith, Malone, Semtner, and Dukowicz.

5. Construction and testing of a 1-degree POP version for tracer studies

Recently, a one-degree version of POP was configured with Smith's help to dynamically model the distribution of additional passive tracers, with initial emphasis on the distributions of F11 and F12 in the ocean. The concentration of these two anthropogenically produced freons has increased consistently in the atmosphere since they were first were introduced around 1930. With knowledge of the solubility of F11 and F12 in the surface waters and the atmospheric concentration as a function of time, the oceanic distributions of these tracers can be modeled using this version of POP. Initially, constant atmospheric concentrations of F11 and F12 were applied and some sensitivity studies were conducted to investigate the importance of different subgrid scale parameterizations, convective adjustment, and varied wind stress forcing with several 10-year simulations. Analysis of these results is ongoing. This activity is continuing on both the NCAR and NCSA CM-5s, thereby incurring no DOE computer costs; and a multi-decadal integration is now being undertaken using realistic time varying forcing of the passive tracers. By comparing the model-determined distributions of F11 and F12 with observations, an assessment of the accuracy and limitations of the dynamics in the model will be possible. These experiments should also lead to a greater understanding of the atmosphere/ocean fluxes of trace gases. This research is being carried out in collaboration with Edward Harrison and John Bullister at NOAA/PMEL.

6. Workshop organization, scientific meetings, and publications

Over the past 2 1/2 years, both Chervin and Semtner have been asked to help organize scientific meetings. A workshop on ocean modeling for the JASON consultants to DOE was organized with their help in October 1992. An upcoming workshop at Los Alamos, featuring parallel ocean modeling for the international WOCE Numerical Experimentation Group, will involve coordination by Semtner as well as CHAMMP investigators from LANL.

Both Chervin and Semtner have participated in numerous national and international meetings, often to give invited talks. For example, they have both attended national and international meetings related to the World Ocean Circulation Experiment, as well as the Fourth International

Conference on the Meteorology and Oceanography of the Southern Hemisphere. They have attended CHAMMP Science Team Meetings, Ocean Predictability Workshops, national meetings of meteorological and oceanographic societies, and Global Change Symposia. They visited numerous university sites such as MIT, Caltech, UCLA, Scripps, Wisconsin, Dartmouth, Princeton, Rutgers, Columbia, and Penn State, as well as various DOE-, NASA-, NOAA- and NSF-sponsored laboratories. Semtner participated in two international meetings on the physical oceanography of the Arctic. Finally, Chervin and Semtner attended the Computerworld-Smithsonian Award Ceremony in Washington, DC, to receive the inaugural award for Leadership in Breakthrough Computational Science, which is sponsored by Cray Research, Inc.

In regard to publications, two papers on heat transport were already mentioned above; and in addition, four published papers have resulted specifically from DOE/CHAMMP support:

- (iii) Semtner, A.J., and R.M. Chervin, 1992: Ocean general circulation from a global eddy resolving model. *J. Geophys. Res.*, 97, 5493-5550.
- (iv) Semtner, A.J., and Chervin, 1993: Including eddies in global ocean models. *EOS, Transactions, American Geophysical Union*, 74, 5, 59.
- (v) McCann, M.P., A.J. Semtner, and R.M. Chervin, 1993: Volume, heat, and salt budgets and transports of a global ocean model with resolved eddies. *Climate Dynamics*, in press.
- (vi) Semtner, A.J., 1993: Very high-resolution estimates of global ocean circulation, suitable for carbon-cycle modeling. *Proceedings of the Snowmass Global Change Institute on the Global Carbon Cycle*, Office of Interdisciplinary Earth Studies, Boulder, in press.

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Wilkin, J.L., and R.A. Morrow, 1994: Eddy kinetic energy and momentum flux in the Southern Ocean: A comparison of Geosat altimeter,